Development of an Integrated Platform for Catchment Management in South Africa

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ABSTRACT

The shift in the balance of knowledge power and the enormous changes in the external business forces operating in the water industry and organisational structures governing water, as well as the National Water Act (NWA) led to the establishment of Catchment Management Agencies (CMAs). Integrated Water Resource Management (IWRM) demands that we take our thinking a step further, since each CMA will have a plethora of conditions/aspects which are required to be managed simultaneously and in an integrated fashion. Due to the complexity of IWRM, water resource managers are unanimous in their opinion that no single simulation model can be used for Integrated Catchment Management (ICM), to the exclusion of others. Therefore, the overall purpose of the project was to design an integrated platform, which provides tools to pre-process data for different independent modelling systems. The objective was to design a Geodatabase where geospatial and temporal data are captured and stored in one environment. The focus was to achieve communication and data exchange between the Geodatabase, HYDSTRA, a hydrological database and BASINS, an environmental analysis system. The Modder River Catchment (MRC), which forms part of the Upper Orange Water Management Area, was used as pilot study area.

Keywords: *integrated catchment management, Geodatabase, GIS, hydrological modelling, water resources.*

1 INTRODUCTION

Water is a scarce resource in South Africa which is characterised by frequent droughts, floods and unevenly distributed precipitation. More than two decades ago, in South Africa, most of the water resources science and management knowledge resided in state departments.

The efficient and sustainable management of water resources have become more important the last few years. The National Water Act (NWA) of 1998 provides a framework to protect water resources against over exploitation. Water is essentially a tool to transform society towards social and environmental justice and poverty eradication. Moreover it is supposed to ensure that there is enough water for social and economic development now and in the future. Today a significant intellect resides with stakeholder groupings that are in contention for water resources. This shift in the balance of knowledge power, and the enormous changes in the external business forces operating in the water industry and organisational structures governing water, as well as the National Water Act (NWA) (DWAF, 1998) led to the establishment of Catchment Management Agencies (CMAs).

CMAs share the responsibility for managing water resources with the state. According to the NWA, 1998, CMAs must manage water resources in a sustainable way by integrating water science, engineering products and services appropriate to national needs. Thus, the core of integration is to understand and manage the dynamics of all these interdependencies which have an impact on the available water resources. The scope and scale of water resources policy and management is enormous and very difficult to put into practice, especially in an integrated fashion. Besides, the amount of available surface- and groundwater, water use, water quality, the coordination of water resource management comprise environmental and social issues which must be integrated (DWAF, 1997; 2000). This can be accomplished through Integrated Water Resources Management (IWRM).

IWRM demands that we take our thinking a step further since each CMA will have a plethora of conditions/aspects which are required to be managed simultaneously and in an integrated fashion (Dent, 2000; 2005). Due to the complexity of IWRM, water resource managers and engineers are unanimous in their opinion that no single simulation model can be used for Integrated Catchment Management (ICM), to the exclusion of others. A vital component in the search for a modelling system for ICM, therefore must be that the system can facilitate inter-operability between time dependent data and the information produced by the different teams. Thus, a Relational Database with all the relevant data (water oriented, environmental, social and political) should then be designed and eventually be converted to a Geodatabase. This would enable CMAs to extract both alphanumeric-, as well as spatial data from the Geodatabase to make decisions. The advances in Geographical Information Systems (GIS) technology have now made it practical to consider far more spatial detail than has been the case. The market is demanding finer and finer spatial resolution. The outputs from the smaller spatial units mean that there is also a demand for finer time scales to be employed. The latter demand brings new challenges to model developers and users (Maidment, 2000a).

Therefore, CMAs must address all time series challenges such as time dependent estimates of environmental attributes (soil type, precipitation, evaporation, geology, temperature, water quantity and -quality) and water supply attributes (industrial needs, human consumption, water demand, water leakage, purification plants) which connects the various interests of the stakeholders in the catchment, externality conflicts, the developed catchment conditions and the actions by contenders for the water resource.

Taking all above-mentioned factors into consideration, it becomes evident that the conventional approach of catchment management as illustrated in Figure 1, must be revised in order to address the far more complex yet necessary job of managing the myriad networks of time series which are generated by the fine spatial scale application of our models. This can be accomplished by integrating ArcGIS, HYDSTRA and the United States Environmental Protection Agency's (USEPA) Better Assessment Science Integrating Point and Non-point Sources (BASINS) as our main platform to work from. According to Maidment (2000) BASINS is the most advanced system presently available for linking GIS, water quality and -quantity modelling and data for the purposes of ICM.

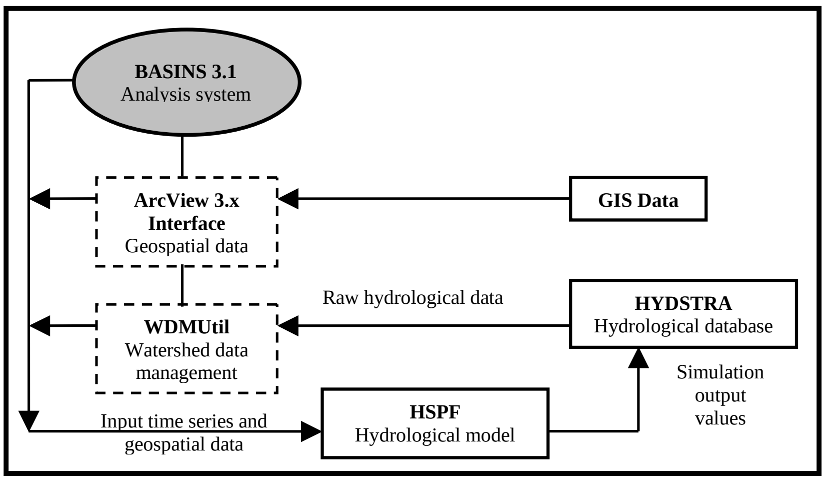

Figure 1: Conventional workflow for catchment management

2 PILOT STUDY AREA

The Modder River Catchment (MRC) (Figure 2) was used as pilot study area. It forms part of the Upper Orange Water Management Area (UOWMA). The Modder River originates in the central Free State and flows in a northerly direction after which it turns to the west. After about 340km the river flows into the Riet River that ends in the Oranje-Vaal River system. The Modder River was initially a seasonal river but due to the construction of three significant dams e.g. Rustfontein-, Mockes- and Krugersdrift Dam the river now resembles a permanent river.

The natural mean annual runoff (MAR) and ecological reserve (ER) of the Modder River Catchment forms 5.8% and 3.3% of the total MAR and ER in the UOWMA respectively. The available water yield of the MRC was 3.1% of the total water yield of the UOWMA in the year 2000. The water requirement, in comparison, was a high of 36.2% of the total water requirement of the UOWMA in that year. Predictions for the year 2025 indicate that there will be an increase in the water requirements of between 14.4 and 24.2%, depending on whether a base- or high case scenario is being evaluated (DWAF, 2004). The relatively high percentage of water requirement compared to the low percentage of available water yield re-emphasises the importance of ICM within the MRC. The catchment is situated in the summer precipitation region and precipitation ranges from about 300mm in the west to about 550mm in the east. The rainy season is from early September to mid April with a dry winter.

The study area is located at an average height of 1200m above mean sea level (MSL) with the highest point at ± 2100m and the lowest at 1100m. 99% of the catchment lies between 1200m and 1400m above MSL. The catchment is characterised by very shallow slopes and water tends to pool easily, thus influencing the attenuation period of floods and high flow conditions. Vegetation is mainly grassland. Some dry land cultivation occurs where the precipitation and soils are favourable, with sizeable areas under irrigation downstream of the main storage dams. The area is geologically very stable and relatively uniform although the geology does dictate the flow to a certain extend.

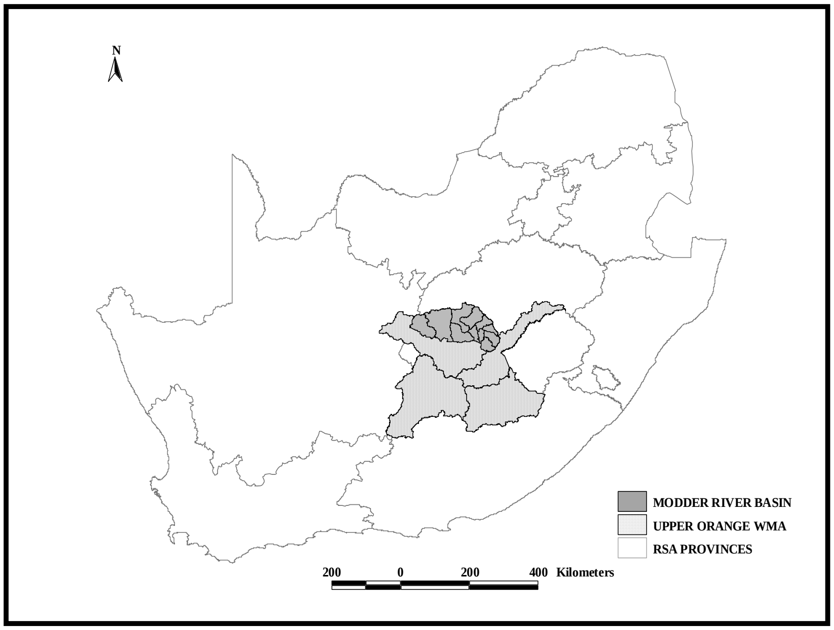

Figure 2: Modder River Catchment

The city of Bloemfontein, as an administrative and commercial centre, is the only large urban development in the MRC. Demographic projections show a small decline in rural population, which is balanced by growth in the Bloemfontein area, resulting in little change in the total population of the catchment within the period of projection. There are also no strong stimulants for economic growth in the catchment (DWAF, 2004).

3 INTEGRATED PLATFORM

The aim of the first phase of the project was to design the Relational Database by making use of Relational Database Management System (RDMS) such as Oracle. This process basically entails the identification of non-spatial entities (population, local and district municipalities, water management agencies) and water related entities (catchment delineation, meteorological- and hydrological stations, rivers and dams), establishment of the entity inter-relationships and creation of an Entity Relational Diagram (ER-diagram, Figure 3) to provide a visual layout of the design.

In the second phase the Relational Database was converted to a Geodatabase, by adding the necessary shape- and metadata files and using it in conjunction with a GIS. The Geodatabase operates within ArcGIS and stores captured geospatial and temporal data of the UOWMA and Middle Vaal Water Management Areas (MVWMAs). Geodatabases can either be designed as a personal- or multi-user Geodatabase. A personal Geodatabase is restricted to project-oriented GIS with Microsoft Access database system as storage medium. A multi-user Geodatabase is a much larger database system with multiple users and simultaneous access possibilities. Thus, the design was based on a multiple user interface to ensure that all stakeholders involved in water resource management can directly or indirectly link to the Geodatabase through a TCP/IP network by making use of ArcSDE (ESRI, 2004). The Geodatabase is then accessed through GIS-based software which allows users to add new data, retrieve data or create graphical representations in a map-based format. Possibilities also exist for information to be made available over the Internet.

In the third phase of the project it was important to achieve communication and data exchange between the Geodatabase (ArcGIS), HYDSTRA and BASINS to create an integrated platform (Figure 4), in order to provide tools to pre-process data for different independent modelling systems. These models can then be used to investigate the impact of changes or developments within the WMAs.

ArcGIS is a combination of multiple integrated GIS software products which was developed for building a complete GIS. ArcGIS, released in 2001, is a synthesis of the powerful Arc/Info system with the easy-to-use interface of ArcView, updated to use the latest advances in desktop computing and database technology. The Geodatabase model arrived with the release of ArcGIS 8. It contains three basic programs, ArcMap, ArcCatalog, ArcToolbox, collectively referred to as ArcGIS Desktop. ArcCatalog with the ArcSDE interface was used as database engine to create the Geodatabase. The ArcGIS Geodatabase forms the top-level unit of geographical data. It is primarily a collection of feature classes, object classes, relationship classes, data sets and attribute data. Geographical data are organised as vector data (features), raster data (images, grid-based thematic data and surfaces) and addresses and locators for finding geographical positions (ESRI, 2004a).

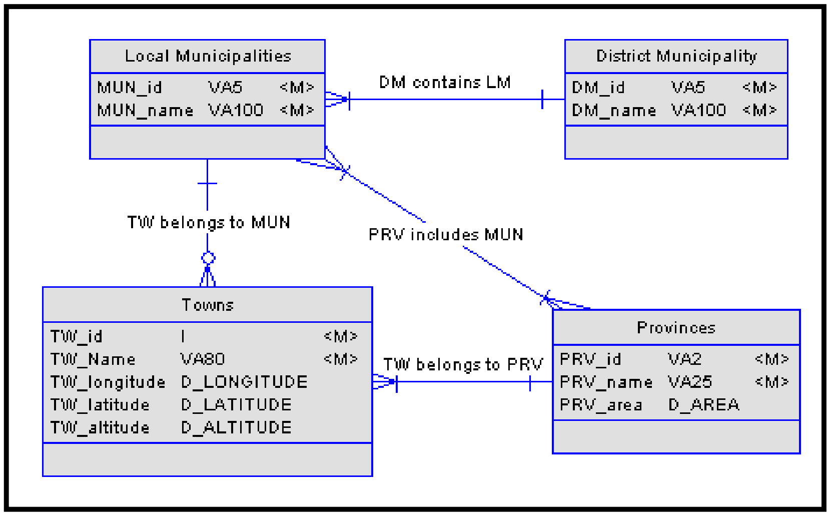

Figure 3: Entity Relationship Diagram

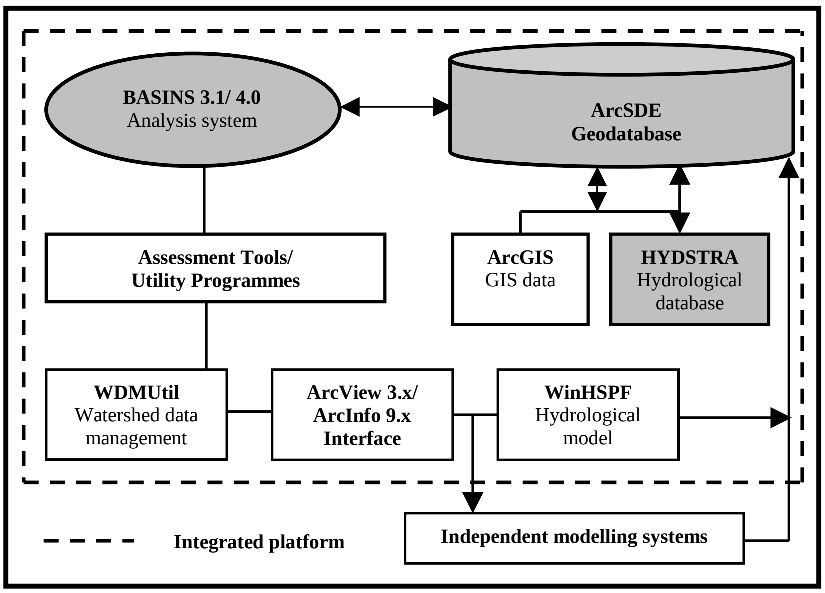

Figure 4: Integrated workflow for catchment management

HYDSTRA is a hydrological database used by the Department of Water Affairs and Forestry (DWAF) and stores all raw hydrological data (flow, precipitation, evaporation etc.) for South African catchments. The automatic link between the Geodatabase and HYDSTRA will ensures that the data in the Geodatabase applicable to the UOWMA and MVWMA are updated on a three monthly basis. The data can then be extracted from the Geodatabase and imported into BASINS.

BASINS has three objectives: To facilitate the examination of environmental information; to support analysis of environmental systems and to provide a platform for examining management alternatives (Battin, 1998; Lahlou *et al*., 1998). The program brings together key environmental data and analysis components in one programme to streamline the many steps involved in catchment based environmental modelling. BASINS contains tools and utility programmes for data synthesis and assessment, as well as for preparing input data for different simulation models. BASINS makes it possible to quickly assess large amounts of data in a format that is easy to use and understand. BASINS also allows the user to assess data at selected locations (gauging stations) or throughout an entire catchment. ArcView GIS is the instrument currently used to bring together the data and analysis. The creation of ArcGIS has provided a springboard to enhance the execution of BASINS' objectives. The capabilities of ArcGIS enable the user to create and maintain data models, thus providing a robust method for organising and presenting the environmental information available in the BASINS database in the form of a data model.

4 RESULTS

The main result which had to be obtained was to design the multi-user Geodatabase and thereafter the creation of the integrated platform, which consists of the Geodatabase, HYDSTRA and BASINS (Figure 4).

The sustainability of the Geodatabase is determined by whether all variables that might have a direct or indirect effect on a WMA were taken into consideration. A large spectrum of data (commercial, network and mission-specific) were obtained from various information sources and stakeholders. Sybase Power Designer was used to create the ER-diagram, information was analysed, mission-critical data was added and some redundant information deleted. Various discussions with individual stakeholders and parties involved led to the final version of the ER-diagram, which formed the basis of the Geodatabase (Figure 5).

Oracle was used as Database Management Structure (DBMS) as it provides the best support to the Spatial Database Engine (SDE) and can handle large amounts of data. The connection with the Oracle DBMS was established through the ArcSDE interface in ArcCatalog. The ArcSDE interface was also used to build the Geodatabase by adding geographical attributes. ArcCatalog is capable of displaying and managing the content of connected databases. All the necessary tables, relationships, domains and business rules were established and created by ArcCatalog. ArcCatalog has the same functionality as Windows Explorer but enables the user to preview geographic data as well as metadata. ArcCatalog also provides the interface between the GIS environment and the Geodatabase.

ArcView 3.2a along with Spatial Analyst and BASINS 3.1 were also used. Digital data were obtained in the form of a set of contour maps of the pilot study area. All the polylines were converted in Arcview 3.2a to points with the extension Poly conversions to spaced points 1.2 with a point every 50m. The data were checked and all errors were removed. Kriging, as an interpolation method with quaternary drift was used for the construction of a Digital Elevation Model (DEM) at 50m-grid size. After the creation of the grid the Fill Sink tool was run on the grid in order to eliminate the sinks that develop between two far removed points. After the creation of the DEM grid (Figure 6) it was converted to a United States Geological Survey (USGS) DEM GRID and added into a BASINS project with a predefined projection.

The digitised river line was then added and the automatic delineation process started by adding the DEM into the calculations and setting up the parameters (meters or degrees) according to which the river will be defined. The digitised river (the program uses the DEM to burn a stream from surface characteristics) due to the unique characteristics of the Modder River. The river line and the DEM were used to derive the sub-catchment areas and the slope. The number of cells was defined to justify a runoff line. The stream outlets were then identified (at the confluence of two streams) and selected to calculate the sub-catchments. All parameters, which influence land cover in terms of vegetation cover (evapotranspiration, water interception), ground cover (type of soil, rock sheet etc.) and soil characteristics (infiltration, soil type) were then fed into BASINS. All these output parameters were then exported to a Watershed Data Management (WDM) file in WDMUtil. Once this platform had been created a link between BASINS and different simulation models were established (Figure 4). The objective is that the platform must be able to link to any independent modelling system. However, we intend to use WinHSPF as hydrological modelling system in our pilot study area. WinHSPF is developed for EPA by Aqua Terra Consultants and distributed with the EPA's BASINS software.

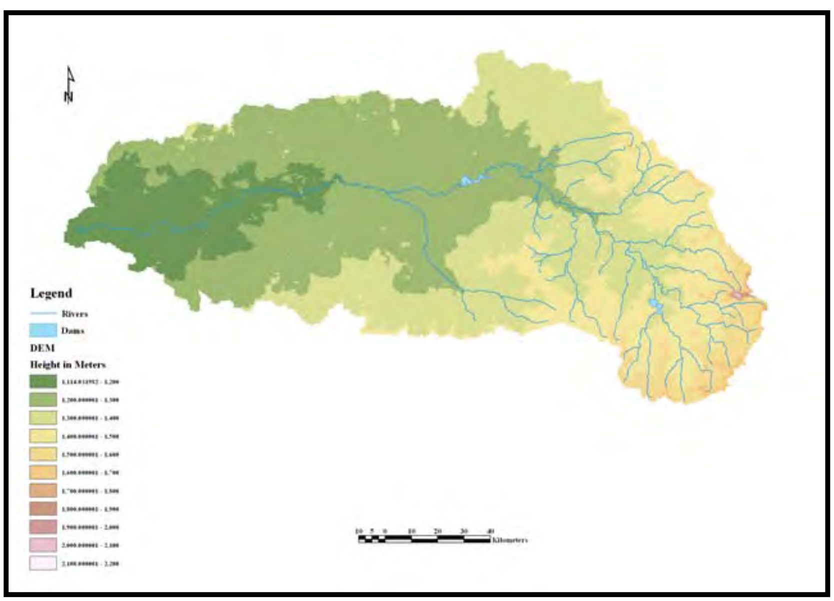

Figure 5: Digital Elevation Model of MRC

5 DISCUSSION AND CONCLUSIONS

Since the design-phase of the Geodatabase is completed and the integrated platform is established, various data can be entered on a continuous basis and preliminary water resource related calculations and simulations can be executed. ArcMap are used to verify the data. This does not however mean that complex simulations and results can be derived from the initial data in the Geodatabase. A trial and error period should be undertaken to validate the data. This period is critical to the whole system and will determine whether the derived information will be reliable and useable. The use of range checks, limits, exception reporting and comparisons will help to identify any anomalies.

Currently some of the input data and parameters for the user input file (.uci) must be developed manually since this process is not automated in BASINS 3.1 for South African data sets. This cumbersome process will be addressed in the new version of BASINS 4.0, which is at present being developed by Aqua Terra Consultants. The new software product in BASINS 4.0, known as the BASINS System Application (BSA) will encompass all of the existing BASINS components and more into a single new interface. Independent access to individual components will still be available, but these components will be tied together into one interface. The BSA will identify which GIS software products are available on the user's computer, and will thus indicate the GIS-based functionality available to the user. This design provides a migration path from the ArcView 3.x components to the ArcView 8.x components.

The BASINS system will be available with limited GIS functionality to a user without either ArcView 3 or ArcGIS. All of the functionality from the BASINS 3 ArcView interface will still be available, while components for ArcGIS can be developed over time and rolled out to the user community. Specific BASINS functionality will require prerequisite GIS products, just as Spatial Analyst is indicated as prerequisite to some functions of BASINS 3.

The extension architecture, integral to BASINS since version 3.0, allows for the addition of other independent modelling systems without re-releasing the core software. This flexible class-based architecture is especially important for the BASINS system, which combines dynamic data sources with a suite of models, thus an ideal system to form the basis of our integrated platform. The data continually evolve, as do the models as different agencies or organisations continually enhance and refine these tools. The software architecture of BASINS 4.0 provides the flexibility needed to keep BASINS always at the leading edge of watershed assessment systems.

One of the most significant enhancements in BASINS 4.0 will be support for ArcGIS 8. A custom GIS interface for BASINS will be available in ArcGIS through a toolbar in ArcMap. The BASINS Toolbar will contain menus for accessing the suite of BASINS GIS functions. The software underlying each menu option in the BASINS toolbar will be packaged as a separate DLL, providing flexibility in the structure of the toolbar, as well as expandability as other tools or models are added in the future. Each menu option will invoke a tool developed in Visual Basic, using the Environmental Systems Research Institute's (ESRI's) ArcObjects for GIS functions. All of the tools and models will share a common component for interacting with ArcObjects. This design enforces a clear separation between tool components and GIS functions. The HSPF tool, known as 'BASINS HSPF for ArcGIS', is the first of the menu options to be implemented (Figure 6). The user interface for this tool was developed using Visual Basic, making use of a number of Visual Basic custom controls and utilities developed for other BASINS tools. Through this interface the user specifies the GIS layers and fields within those layers to be used in setting up a new HSPF project.

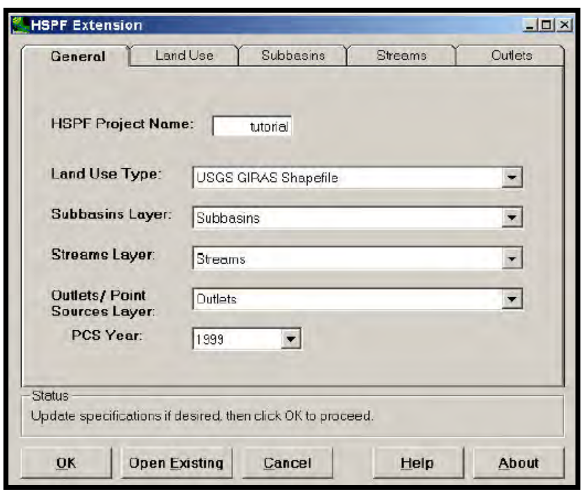

Figure 6: BASINS HSPF for ArcGIS

Recommendations for future refinements of the integrated platform are as follows:

- Expand the Geodatabase so that the data are applicable to both the UOWMA and MVWMA. Communication and data exchange must also be established with other existing ESRI Geodatabases at other universities or organisations involved in IWRM.
- Hydrological data (flow, precipitation, evaporation, etc.) as we all know are public domain and nowadays can be downloaded from the internet. At this stage we are lagging behind countries such as America where data are automatically downloaded from the internet into a database such as HYDSTRA or BASINS. The aim will then be to automate the process is such a way that the modeler does not have to waist time by downloading and converting data to a certain format.
- As soon as BASINS 4.0 is available, it will be incorporated into the integrated platform, in order to enhance the workability/practicality thereof (Figure 2). It will furthermore improve the communication and data exchange between the platform and the independent modelling systems. In this integrated platform stakeholders will be able to import raw data by means of data exchange between HYDSTRA and the Geodatabase, then data will be transformed in the Geodatabase and exported to BASINS to be utilised in ICM and decision-based simulations.
- Verify the accuracy of all the observed data in the UOWMA and MVWMA by evaluating all aspects of flow measurement. The methods of measuring, type of structures, instrumentation and processing will be scrutinised and evaluated. Problem areas will be identified such as sediment, vandalism and incorrect site selection which influence the accuracy of the measurements. In short a true and realistic opinion will be given of the state of flow measurement in the WMAs, which will assist the modeler in the initial calibration of the independent modelling system in use.
- Development of DEMs of all the catchments of concern in the WMAs.
- Collect and develop more representative river geometry data by means of HEC-RAS in order to improve the stage-discharge relationships and to expand the FTABLES (Function Tables) in WinHSPF, especially when in-depth water quality studies are to be performed in future. Many water quality processes depend on river depth. Currently, the river cross-sections used to compute the stage-discharge relationships in HSPF were based on very limited data, *viz.* GIS data, topographical maps, orthographical photographs and topographical- and section surveys.
- The application of HEC-RAS to analyse the flow conditions in the river reaches, as well as the effects of submergence on the accuracy of flow measurement.
- The application of WinHSPF in both the UOWMA and MVWMA to do hydrological- and water quality simulations. Additionally, investigate the use of Conditional Special Actions (CSA), water categories and –allocation and how it relates to the implementation of the NWA, 1998.
- The use of PEST, a model-independent, non-linear parameter estimator to improve the final calibrated values (Doherty *et al.*, 1994). PEST also allows confidence limits to be set on parameter estimates, allowing for a more reliable application of the model as a predictive tool.

People can no longer waste water. The state, water boards, municipalities and many other stakeholders should become actively involve in IWRM. Finally we hope that it will contribute to the open source revolution which starts to characterise the water modelling world, as firstly initiated by the USEPA BASINS development. This will lead to new opportunities for the more effective analysis of catchment management.

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